

Anisotropic flow of strange particles at RHIC

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Abstract. Space-time picture of the anisotropic flow evolution in Au+Au collisions at BNL RHIC is studied for strange hadrons within the microscopic quark-gluon string model. The directed flow of both mesons and hyperons demonstrates wiggle structure with the universal antiproton slope at $|y| \leq 2$ for minimum bias events. This effect increases as the reaction becomes more peripheral. The development of both components of the anisotropic flow is closely related to particle freeze-out. Hadrons are emitted continuously, and different hadronic species are decoupled from the system at different times. These hadrons contribute differently to the formation and evolution of the elliptic flow, which can be decomposed onto three components: (i) flow created by hadrons emitted from the surface at the onset of the collision; (ii) flow produced by jets; (iii) hydrodynamic flow. Due to these features, the general trend in elliptic flow formation is that the earlier mesons are frozen, the weaker their elliptic flow. In contrast, baryons frozen at the end of the system evolution have stronger v_2 .

1. Introduction

The transverse collective flow of particles is usually decomposed onto isotropic radial flow and anisotropic components, such as directed flow, elliptic flow, etc. Directed and elliptic flows are defined as the first and the second harmonic coefficients, v_1 and v_2 , of an azimuthal Fourier expansion of the particle invariant distribution [1]

$$E \frac{d^3 N}{d^3 p} = \frac{1}{\pi} \frac{d^2 N}{dp_t^2 dy} [1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \dots] , \quad (1)$$

where ϕ is the azimuthal angle between the transverse momentum of the particle and the reaction plane, and p_t and y is the transverse momentum and the rapidity, respectively. The directed and elliptic flows can be presented as

$$v_1 \equiv \langle \cos \phi \rangle = \left\langle \frac{p_x}{p_t} \right\rangle , \quad v_2 \equiv \langle \cos 2\phi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle . \quad (2)$$

with x being the impact parameter axis. The transverse momentum of a particle is simply $p_t = \sqrt{p_x^2 + p_y^2}$.

The overlapping area of two nuclei colliding with non-zero impact parameter b has a characteristic almond shape in the transverse plane. The fireball tries to restore spherical shape, provided the thermalization sets in rapidly and the hydrodynamic description is appropriate [2]. When it becomes spherical, apparently, the elliptic flow stops to develop. Therefore, v_2 can carry important information about the earlier

phase of ultrarelativistic heavy-ion collisions, equation of state (EOS) of hot and dense partonic matter, and is expected to be a useful tool to probe the formation and hadronization of the quark-gluon plasma (QGP).

2. Directed and Elliptic Flow

Figure 1 shows the rapidity dependence of the directed flow of ϕ , N , and K in minimum bias Au+Au collisions at $\sqrt{s} = 130$ AGeV. The slopes of the all distributions are negative at $|y| \leq 2$, i.e. the antiflow component of the v_1 dominates over its normal counterpart (see [3]). Similar antiflow slopes of $v_1(y)$ are developed by π and Λ [3,4]; its origin is traced to nuclear shadowing. At midrapidity $|y| \leq 0.5$ the directed flow of all hadrons is quite weak. Figure 2 depicts the simulation results for the $v_1(\eta)$ of charged hadrons compared to the experimental data from the PHOBOS [5] Collaboration for 6% to 55% central Au+Au collisions at $\sqrt{s} = 200$ AGeV. One can see that the model

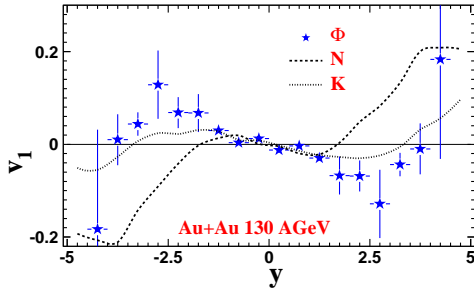


Figure 1. Directed flow $v_1(y)$ of ϕ, N, K in minimum bias Au+Au events at $\sqrt{s} = 130$ AGeV.

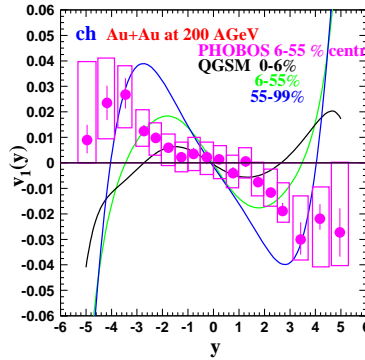


Figure 2. Centrality dependence of the $v_1^{ch}(\eta)$ in Au+Au collisions at $\sqrt{s} = 200$ AGeV.

reproduces the v_1 data quite well both qualitatively and quantitatively, although the maxima of the directed flow around $|\eta| \approx 2$ are shifted to lower pseudorapidities compared to the experimental data. Similar antiflow alignment can be obtained also within the multi module model (MMM) [6], which is based on fluid dynamics coupled to formation of colour ropes. Microscopic models based on FRITIOF routine, e.g. UrQMD and AMPT, show a very flat and essentially zero directed flow [7,8] in a broad range $|\eta| \leq 2.5$. Although the data seem to indicate antiflow behaviour for the directed flow of charged particles with the possible flatness at $|\eta| \leq 1.5$, the measured signal is quite weak, – the magnitude of the flow is less than 1% at $|\eta| \leq 2$. Therefore, relatively large systematic error bars do not permit us to disentangle between the different models. The other features which should be mentioned here are broadening of the antiflow region and increase of its strength as the reaction becomes more peripheral.

Microscopic models based on string phenomenology and transport theory are able to reproduce many features of the elliptic flow at ultrarelativistic energies [7,9,10]. However, the quantitative agreement with the data is often not so good. Particularly,

magnitude of the distributions $v_2(\eta)$ or $v_2(p_t \geq 1.5 \text{ GeV}/c)$ appears to be too high. Does it mean that the effective EOS of hot and dense partonic-hadronic matter in microscopic models is too soft? Then, the microscopic calculations [11] show the absence of sharp freeze-out of particles in relativistic heavy-ion collisions. What are the consequences of the continuous freeze-out for the v_2 of these particles? To study the development of the elliptic flow ca. $20 \cdot 10^3$ gold-gold collisions with the impact parameter $b = 8 \text{ fm}$ were generated at $\sqrt{s} = 130 \text{ AGeV}$. According to previous studies [10, 12] the elliptic flow of charged particles is close to its maximum at this impact parameter, and the multiplicity of secondaries is still quite high. The time evolutions of the v_2 of kaons and lambdas as functions of rapidity are displayed in Fig. 3(a). Here the snapshots of the v_2 profile are taken at certain time $t = t_i$, when all hadronic interactions are switched off and particles are propagated freely. To avoid

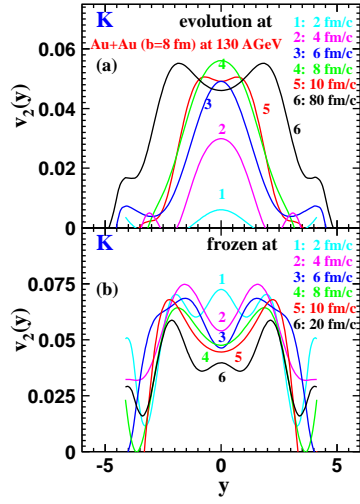


Figure 3. $d^2N/dx dy$ distributions for Λ and K in Au+Au collisions with $b = 8 \text{ fm}$ at $\sqrt{s} = 130 \text{ AGeV}$.

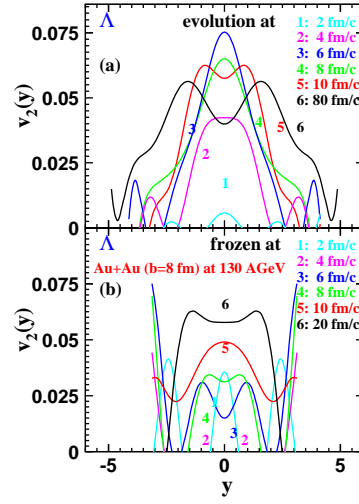


Figure 4. $d^2N/dp_x dp_y$ distributions for Λ and K in Au+Au collisions with $b = 8 \text{ fm}$ at $\sqrt{s} = 130 \text{ AGeV}$.

ambiguities, resonances were allowed to decay according to their branching ratios. Surprisingly, at $t = 2 \text{ fm}/c$ elliptic flow of kaons is weak. The flow continuously increases and reaches its maximum value $v_2^K(y = 0) \approx 6\%$ already at $t = 8 \text{ fm}/c$. From this time the elliptic flow does not increase anymore. Instead, it becomes broader and develops a two-hump structure with a relatively weak dip at midrapidity. The flow seems to continue development till the late stages of the system evolution. However, the contributions of survived particles to the resulting elliptic flow presented in Fig. 3(b) reveal the peculiar feature: the v_2 of kaons, which are frozen already at $t = 2 \text{ fm}/c$, is the **strongest** among the fractions of the flow carried by kaons decoupled from the fireball later on. The later the kaons are frozen, the weaker their flow. One can conclude that the strong elliptic anisotropy of kaons, which left the system early, is caused by the absorption of kaons in the squeeze-out direction.

For lambdas the evolution picture of the $v_2(y)$, shown in Fig. 4(a), is similar to that for kaons. The flow is quite weak at $t = 2 \text{ fm}/c$, then it increases and gets a full

strength at midrapidity between 8 fm/c and 10 fm/c, i.e. later than the elliptic flow of kaons. Similarly to $v_2^K(y)$, it develops a two-hump structure, but the humps tend to dissolve at late stages of system evolution. In contrast to this behavior, the freeze-out decomposition picture of $v_2^\Lambda(y)$, presented in Fig. 4(b), does not show monotonic tendency within first 8 fm/c of the reaction: The flow of Λ frozen at 2 fm/c is identical to that of Λ frozen at 8 fm/c, whereas lambdas decoupled from the system between 2 fm/c and 8 fm/c almost do not contribute to the resulting elliptic flow. Lambdas, which are decoupled after 8 fm/c, have significant anisotropy in the momentum space, and the later the lambdas are frozen, the **stronger** their elliptic flow. This picture is similar to that obtained for the development of pionic and nucleonic elliptic flows [13].

3. Conclusions

In summary, the features of the formation and development of anisotropic flow in gold-gold collisions at RHIC in the microscopic quark-gluon string model can be stated as follows. (1) The directed flow of all hadrons exhibits antiflow alignment within the pseudorapidity range $\eta \leq 2$. The signal increases as the reaction becomes more peripheral. At midrapidity $|\eta| \leq 1$, however, the generated flow is quite weak and consistent with zero-flow behaviour reported by the STAR and PHOBOS collaborations. (2) There is no one-to-one correspondence between the apparent elliptic flow and the contribution to the final flow coming from the “survived” fraction of particles. For instance, apparent elliptic flow of kaons at $t = 2$ fm/c is weak, but kaons which are already decoupled from the system at this moment have the strongest elliptic anisotropy caused by their absorption in the squeeze-out direction. Elliptic flow of hadrons is formed not only during the first few fm/c, but also during the whole evolution of the system because of continuous freeze-out of particles. (3) The time evolutions of the mesonic flow and baryonic flow are quite different. The general trend in particle flow formation in microscopic models at ultrarelativistic energies is that the earlier mesons are frozen, the weaker their elliptic flow. In contrast, baryons frozen at the end of the system evolution have stronger v_2 . Therefore, development of particle collective flow should not be studied independently of the freeze-out picture.

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